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FUZZY-PID METHODS FOR CONTROLLING EVAPORATOR SUPERHEAT

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ABSTRACT
A new method is proposed to control the evaporator’s superheat with an electronic-expansion-valve (EEV). The conventional PID control with invariable parameters can not receive sound performance because of the variation of evaporators’ characteristic parameter under disturbances. To solve this problem, fuzzy algorithm is utilized to adjust parameters of PID control on line, two practical methods are given and both are performed in experiments. It is found that fuzzy-PID greatly reduced the time to reach steady state, the error (±0.3°C) is much smaller than that of conventional PID, which is ±1°C. The hardware and software of fuzzy-PID are no more complex than those of conventional PID. By use of fuzzy-PID, the control performance is improved, but the cost does not increase.

INTRODUCTION
Control of the degree of evaporator superheat is an important aspect in refrigeration system control, because it affects efficiency and safety of system directly. The performance of a controller depends on the matching of controller’s characteristic to the object. To get good control effect, it is necessary to be acquainted with object’s characteristic. Generally, a first-order lag plus time delay model is used to describe an evaporator, it is found that the characteristic parameters in the model alter accordingly with the variation of operating condition. With theoretical analysis and practical experiments, the evaporator’s response to variation of refrigerant flow rate and load is observed. Because of its simplicity, robustness and accuracy, PID control is often used for air conditioners and refrigeration machines. But the parameters of conventional PID will not change once they have been defined. At the same time, PID is a linear control method and it can not take satisfactory effects on the highly nonlinear object. Fuzzy control does not need the accurate mathematical model of controlled object and it can also perform very well in multivariable, nonlinear and time-varying systems. But sometimes its accuracy does not meet requirement, it is only a coarse controller. In consideration of individual merits and drawbacks of them, in this paper, these two methods are combined, the fuzzy algorithm is implemented to adjust PID parameters on line in order to improve the applicability of PID.

EVAPORATOR DYNAMIC CHARACTERISTICS
Some researchers think the response of superheat to variation of refrigerant flow in an evaporator is a first-order lag process, $G(s) = \frac{K}{1+Ts}$, $K$ and $T$ change with evaporation temperature and refrigerant flow.

Here, the evaporator is treated as a first-order lag plus time delay object, its transfer function can be expressed...
as:

\[ G(s) = \frac{\Delta T}{M} = \frac{K \cdot e^{-\tau}}{1 + T_p s} \]  

(1)

Where \( K \) is the evaporator gain, \( T_p \) is the time constant, \( \tau \) is the delay and \( s \) is the Laplace operator.

A. OUTTAGARTS observed the variation tendency of these parameters and pointed out that they are function of evaporation temperature \( T_e \) and compressor rotation speed \( N \).[1]

In this paper, from evaporator's open-loop response to a step excitation, we can get the characteristic parameters according to Cohn-Coon formula.

\[
\begin{align*}
K &= \frac{\Delta(\Delta T)}{\Delta M} \\
T_p &= 1.5(t_{0.632} - t_{0.28}) \\
\tau &= 1.5(t_{0.28} - t_{0.632}/3)
\end{align*}
\]  

(2)

Where, \( \Delta M \) - evaporator flow step excitation;

\( \Delta(\Delta T) \) - evaporator superheat response;

\( t_{0.28} \) - time for superheat to get 0.28 \( \Delta(\Delta T) \) in evaporator's response curve;

\( t_{0.632} \) - time for superheat to get 0.632 \( \Delta(\Delta T) \) in evaporator's response curve;

Because the degree of opening of the electronic expansion valve driven by stepper motor is nearly linear to refrigerant mass flow, and the motor move rapidly, the evaporator gain can be expressed as the ratio between variation of superheat and pulses imposed to the stepper motor:

\[ K = \frac{\Delta(\Delta T)}{\Delta n} . \]

The time constant \( T_p \), is related to heat transfer coefficient and thermal inertia of the evaporator, as are the function of thermal resistance \( R \) and thermal capacitance \( C \): \( T_p = RC \). Thermal resistance \( R \) is the function of heat transfer coefficient outside evaporator \( \alpha_o \) and inside the evaporator \( \alpha_i \). \( \alpha_i \) is related to refrigerant mass flow rate \( v_o \), heat flow density \( q_i \). \( \alpha_o \) is related to cooled fluid Reynolds number \( Re \), Prandtl number \( Pr \), so we can get:[4]

\[ R = f(q_i, v_o, Re, Pr). \]

(3)

The thermal capacitance \( C \) includes three parts, the evaporator's metal structure \( C_1 \), refrigerant \( C_2 \) and cooled fluid \( C_3 \). \( C_1 \) and \( C_3 \) are constant after the evaporator has been constructed. \( C_2 \) is related to distribution, density, specific enthalpy of refrigerant and inner volume of a evaporator, it will keep constant when the structure of evaporator has been defined. So \( T_p \) can be expressed as following:

\[ T_p = f(q_i, v_o, Re, Pr) \]

(4)

Time delay \( \tau \) is the time for refrigerant flowing through the evaporator, it is decided by refrigerant
flow rate and length of evaporator. \( \tau \) comprises the pure delay \( \tau_0 \) and the volume delay \( \tau_c \). \( \tau_0 \) is the delay caused from signal transmission, which relies on the flow rate of refrigerant and the length of evaporator, the lower the flow rate is, the longer the \( \tau_0 \) is. Volume delay \( \tau_c \) is caused by the volume of evaporator. Because of the metal tube between refrigerant and cooled fluid, the heat transfer between them must first overcome the thermal resistance of metal tube. When the evaporator structure is fixed, \( \tau_c \) is constant. So, \( \tau = f(v_0, l) \).

As stated above, \( K \) can be expressed as the ratio of variation between superheat \( \Delta T' \) and flow \( M \). It is related to the refrigerant flow rate. From above analyses, it is shown that there are many factors affecting the evaporator’s characteristics \( T_p, \tau \) and \( K \). First, they are related to system configuration and evaporator structure. Secondly, they are affected by operating condition of system and flowing condition of refrigerant. Because these factors is changing continuously in operation, the evaporator’s characteristics will vary accordingly.

**FUZZY-PID ALGORITHM**

**PID control**

The digital PID control can be implemented by the following:

\[
\Delta u(k) = K_p (e(k) - e(k-1)) + \frac{T}{T_i} e(k) + \frac{T_d}{T} [e(k) - 2e(k-1) + e(k-2)]
\]

(5)

\[
\Delta u(k) = u(k) - u(k-1)
\]

(6)

Where, \( e \) -the error between the measured value and set value, \( u \) -controller output, \( K_p \) -proportional constant, \( T_i \) -integral constant, \( T_d \) -derivative constant, \( T \) -sampling time, \( k \) -sampling ordinal number.

In practical control, \( \Delta u(k) \) corresponds to the pulse imposed to the stepper motor. Coefficients \( K_p, T_i \) and \( T_d \) are calculated from Ziegler-Nichols formula and they will not vary once have been obtained. It is evident that the conventional PID is not fit for controlling such objects with variable parameters. But because of its robustness, sometimes it can also take good effect in the case of object’s being nonlinear. But from theoretical analyses and practical experiments, it is observed that evaporators’ dynamic characteristic will change largely due to the variation of operating condition and outside disturbances. In order to obtain sound control performance, the coefficients of PID should be adjusted on line. [2][3]

**Adjustment using fuzzy method**

Here, tracking error \( e \), the error between the measured superheat and set value, and \( de \) which is the rate of change of \( e \) are used as input variables. According to the variation of these two inputs, the PID parameters are tuned using fuzzy algorithm. But if these three coefficients are adjusted simultaneously, the inference rules
will be very complex and the experience is incomplete. To solve this problem, two methods are proposed.

**Method 1**

The PID formula is first simplified with Z-N formula or critical proportion method. For example, according to critical proportion method, put the values of control degree being 1.05 into equation (5):

\[
\Delta u(k) = K_p[11.029e(k) - 21e(k-1) + 10e(k-2)]
\]  

(7)

<table>
<thead>
<tr>
<th>Control degree</th>
<th>controller</th>
<th>( T )</th>
<th>( K )</th>
<th>( Ti )</th>
<th>( Td )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.05</td>
<td>PI</td>
<td>0.03( Tr )</td>
<td>0.53 ( Kr )</td>
<td>0.88 ( Tr )</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.014( Tr )</td>
<td>0.63 ( Kr )</td>
<td>0.49 ( Tr )</td>
<td>0.14( Tr )</td>
</tr>
<tr>
<td>1.2</td>
<td>PI</td>
<td>0.05( Tr )</td>
<td>0.49 ( Kr )</td>
<td>0.91 ( Tr )</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.043( Tr )</td>
<td>0.47 ( Kr )</td>
<td>0.47 ( Tr )</td>
<td>0.16( Tr )</td>
</tr>
<tr>
<td>1.5</td>
<td>PI</td>
<td>0.14( Tr )</td>
<td>0.42 ( Kr )</td>
<td>0.99 ( Tr )</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>PID</td>
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<td>0.34 ( Kr )</td>
<td>0.43 ( Tr )</td>
<td>0.2( Tr )</td>
</tr>
<tr>
<td>2.0</td>
<td>PI</td>
<td>0.22( Tr )</td>
<td>0.36 ( Kr )</td>
<td>0.05 ( Tr )</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>PID</td>
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<td>0.27 ( Kr )</td>
<td>0.4( Tr )</td>
<td>0.22( Tr )</td>
</tr>
</tbody>
</table>

Table 1  PID parameters according to critical proportion method
Where \( Tr \)-ultimate period, \( Kr \)-ultimate gain.

So there is only one parameter \( K_p \) in the equation. In real time control, \( K_p \) is adjusted continuously on line with fuzzy reasoning. First, \( e \) and \( de \) must be transformed to \( E \) and \( dE \) in the universe of discourse. of \( E \) and \( dE \) are the same, \([-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6]\) According to magnitude and sign, seven subsets are defined on the universes of discourse, \{PL,PM,PS,ZO,NS,NM,NL\}. Universe of discourse of \( K_p \) is, \([0,1,2,3,4,5,6,7,8,9,10,11,12,13]\), four fuzzy subsets are defined, \{ZO,PS,PM,PL\}. The reasoning rules are worked out as follows:

- IF \( E \) is NL(PL) and \( de \) is NL or NM(PL or PM), THEN \( K_p \) is PL;
- IF \( E \) is NL(PL) and \( de \) is NS(PS), THEN \( K_p \) is PM;
- IF \( E \) is NL(PL) and \( de \) is ZO or PS(ZO or NS), THEN \( K_p \) is PS;
- IF \( E \) is NM(PM) and \( de \) is NL or NM(PL or PM), THEN \( K_p \) is PM;
- IF \( E \) is NM(PM) and \( de \) is NS(PS), THEN \( K_p \) is PS;
- IF \( E \) is NM(PM) and \( de \) is ZO or PS(ZO or NS), THEN \( K_p \) is ZO;
- IF \( E \) is NS(PS) and \( de \) is NL or NM(PL or PM), THEN \( K_p \) is PS;
- IF \( E \) is NS(PS) and \( de \) is NS(PS), THEN \( K_p \) is PS;
- IF \( E \) is NS(PS) and \( de \) is ZO or PS(ZO or NS), THEN \( K_p \) is ZO;
- IF \( E \) is ZO and \( de \) is NL or PL, THEN \( K_p \) is PS.
A fuzzy control table can be established based on these rules. In operation, according to measured E and dE, we can get an optimum $K_p$ by looking up table 2.

<table>
<thead>
<tr>
<th>$K_p$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6</td>
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<tr>
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<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2  Fuzzy control table based on method 1

Method 2

In method 1, only proportion coefficient is adjusted. Intending to get better effect, another method is proposed. Because the derivative term has little effect on the thermal control systems[3], derivative coefficient is supposed to be constant.

A correction coefficient, $\theta$, is introduced. $K_p$, $T_i$ and $T_d$ are expressed as following:[5]

$$K_p = K_{p0} \frac{1}{\gamma \beta}, \quad T_i = T_{i0} \frac{\beta (1 + \theta)}{2}, \quad T_d = T_{d0}$$

(8)

$\gamma$ is proportional gain, $\beta$ is integral gain. $\theta$ is obtained from fuzzy reasoning. $K_{p0}, T_{i0}$ and $T_{d0}$ are initial value, which can be got from Z-N formula. According to E and dE, another fuzzy variable, H, is introduced. H reflects the variation tendency of $\theta$ in dynamic process. Fuzzy control quantity H must be converted into ordinary quantity $h(t)$, which is used to adjust $\theta$ on line, so we can get equation (9):

$$\theta(t) = \theta(t-1) + \eta \cdot h(t), \quad \theta(t) \in (0,1)$$

(9)

$\eta$ is a positive constant, as used to regulate the rate of change of $\theta$. Here, $\eta = 0.1, \theta(0) = 1$

As method 1, seven subsets are defined for E and dE. The universe of discourse of H is {-2,-1,0,1,2}. According to control table 3, defuzzify H and put it into equation (9). After getting $\theta(t)$, coefficients can be
adjusted from equation (8).

<table>
<thead>
<tr>
<th>$H$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6</td>
<td>2</td>
</tr>
<tr>
<td>-5</td>
<td>2</td>
</tr>
<tr>
<td>-4</td>
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<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>3</td>
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<tr>
<td>4</td>
<td>-2</td>
</tr>
<tr>
<td>5</td>
<td>-2</td>
</tr>
<tr>
<td>6</td>
<td>-2</td>
</tr>
</tbody>
</table>

Table 3  Fuzzy control table based on method 2

EXPERIMENTAL RESULTS

The characteristics parameters obtained from figure 1 are: $T_p = 95s$, $\tau = 26s$, $K = 0.33$. From figure 2, we can get $T_p = 44s$, $\tau = 12s$, $K = 0.048$. Comparing these two figures, it is found that $T_p$, $\tau$ and $K$ will decrease when the opening degree of EEV increases. This is because that small opening degree leads to the low refrigerant flow rate, the heat transfer coefficient become small and the thermal resistance get big. For this reason, the time constant $T_p$ and $\tau$ are big. When the flow rate is low, much of heat transfer area is not used, $\Delta T$ is sensitive to $M$, $K$ is big. The increase of flow rate leads to littler sensitivity of $\Delta T$ to $M$, which is because that the increasing proportion of area of evaporator being used will decrease the sensitivity. So it is
observed that the gain $K$ will decrease with the increase of flow rate $v_0$.

In figure 3, an electrical heater is added to increase the heat load of evaporator. It is shown that $T_p = 59s$, $\tau = 12s$, $K = 0.094s$. Comparing with figure 2, $T_p$ and $K$ become big, and $\tau$ is almost steady. This is because the heater enlarged evaporator’s thermal inertia, the thermal resistance and capacity is thus increased. Because refrigerant flow rate didn’t vary, the time delay almost keep constant.

![Figure 3](image1.png)

**Figure 3** With heater, evaporator’s response to a step of opening degree of EEV from 140-180

![Figure 4](image2.png)

**Figure 4** Superheat control using PID algorithm

![Figure 5](image3.png)

**Figure 5** Superheat control using fuzzy algorithm, method 1

![Figure 6](image4.png)

**Figure 6** Superheat control using fuzzy algorithm, method 2

Figure 4 expresses the control performance of PID. It is apparent that the superheat is also oscillating around the set value, the control is unsteady. Figure 5, 6 show the performance using above mentioned two fuzzy methods. The overshoot is not reduced because no special algorithm is used but the opening of EEV in a set value during start-up and the overshoot is even bigger using method 1. Comparing with the conventional PID, time to reach the steady state is reduced from 400 seconds to 200 seconds, the static superheat is reduced.
from ± 1°C to ± 0.3°C and the control is pretty steadier than conventional PID. As a summary, it is evident that fuzzy-PID can take better effects.

CONCLUSION

From the response curve obtained in experiments, it is verified that a evaporator can be regarded as a first-order lag plus time delay object. But due to the strong coupling of parameters, which will lead to the high nonlinearity of an evaporator, the characteristic parameters in the mathematical model is much variable. Besides operating condition, the refrigerant flow and heat load can affect them strongly. The characteristic parameters $T_p, K, \tau$ will decrease with the increase of refrigerant flow and the heat load will increase $T_p, K$.

Using fuzzy algorithm to adjust PID parameters is feasible. This method is suited to the evaporator's characteristic. In fact it nonlinearize the conventional PID, so fuzzy-PID can receive good performance in controlling the object with high nonlinearity such as evaporators. Only a fuzzy subroutine is added to the conventional PID, as is easy to achieve. Experiments show although the opening of EEV is invariable during start-up, the time to reach steady state and error are reduced greatly.

Because derivative term has little effect on control, it is feasible to keep an invariable derivative coefficient when adjusting PID coefficients. Sometimes the control can receive good performance only by adjusting the proportional coefficient, this is because the proportional action is the most important in control and the integral and derivative action is also adjusted at the same time.

REFERENCES